EE 435

Lecture 28

Data Converters

- INL of ADCs
- Differential Nonlinearity
- Spectral Performance

Performance Characterization of Data Converters

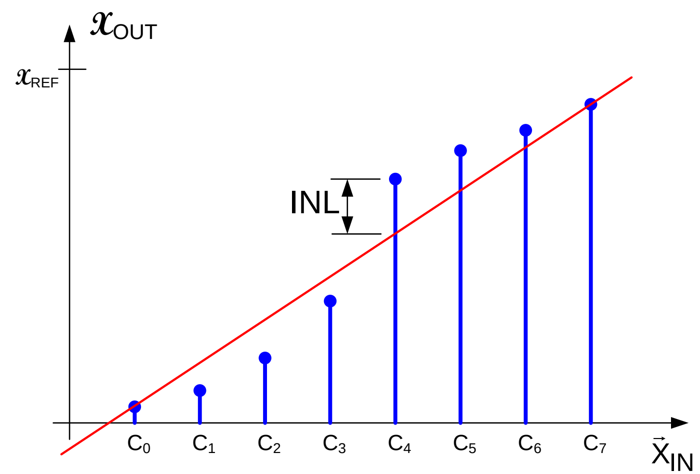
Review from last lecture

- Static characteristics
  - Resolution
  - Least Significant Bit (LSB)
  - Offset and Gain Errors
  - Absolute Accuracy
  - Relative Accuracy
  - Integral Nonlinearity (INL)
  - Differential Nonlinearity (DNL)
  - Monotonicity (DAC)
  - Missing Codes (ADC)
  - Low-f Spurious Free Dynamic Range (SFDR)
  - Low-f Total Harmonic Distortion (THD)
  - Effective Number of Bits (ENOB)
  - Power Dissipation

Integral Nonlinearity (DAC)

Review from last lecture . . . .

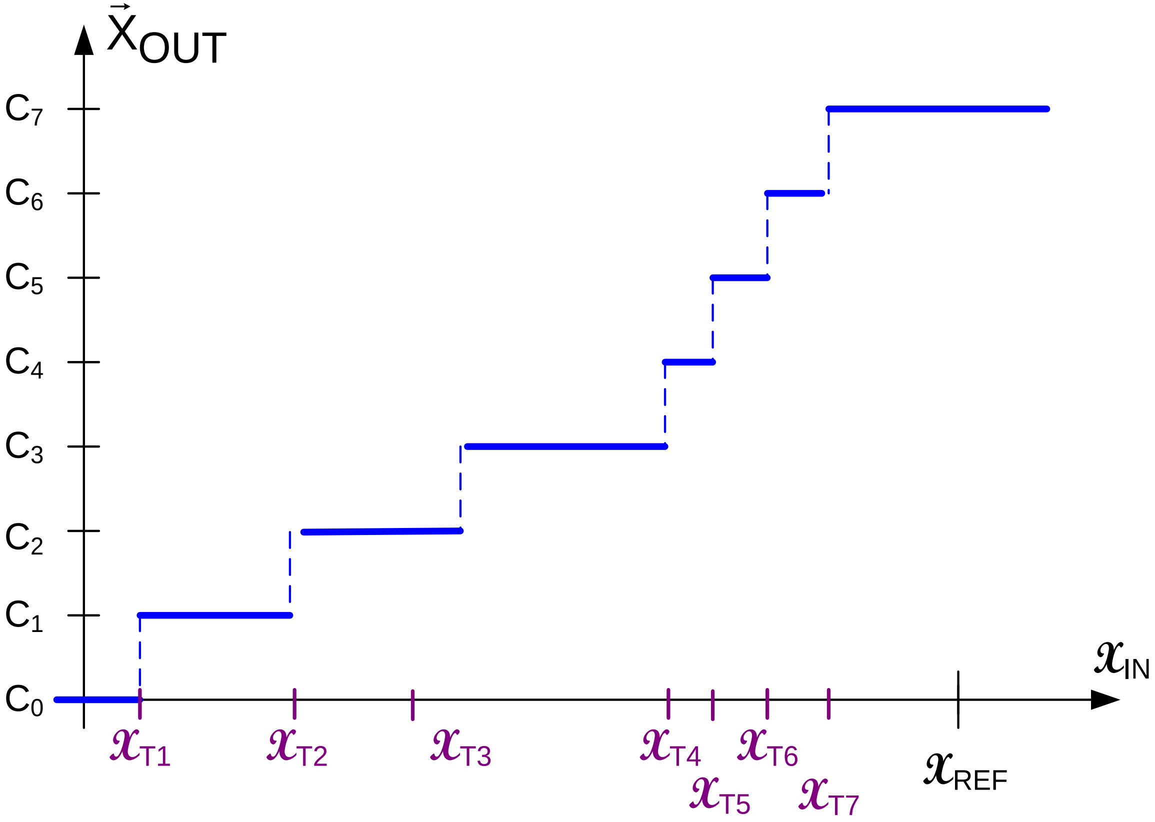
Nonideal DAC



- At design stage, INL characterized by standard deviation of the random variable
- Closed-form expressions for INL almost never exist because PDF of order statistics of correlated random variables is extremely complicated
- Simulation of INL very time consuming if n is very large (large sample size required to establish reasonable level of confidence)
  - Model parameters become random variables
  - Process parameters affect multiple model parameters causing model parameter correlation
  - Simulation times can become very large
- INL can be readily measured in laboratory but often dominates test costs because of number of measurements needed when n is large
- Expected of INL_k at k=(N-1)/2 is largest for many architectures
- Major effort in DAC design is in obtaining acceptable yield !

Integral Nonlinearity (ADC)

Nonideal ADC

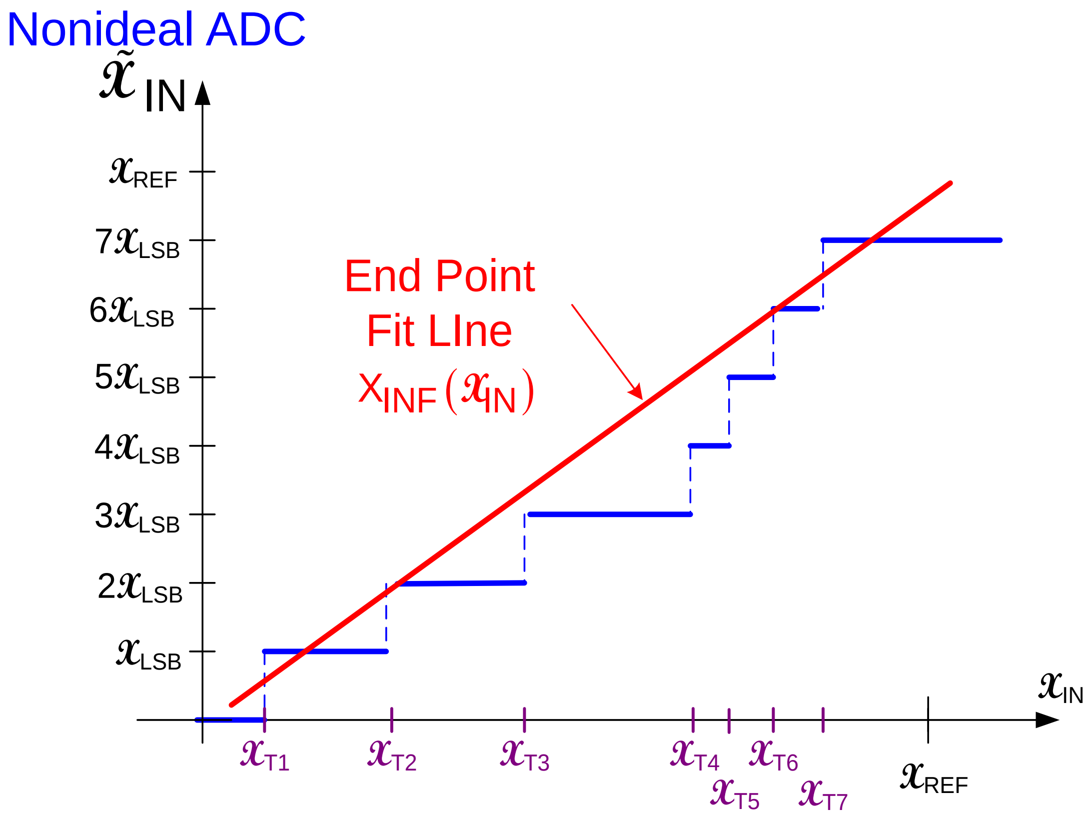


Transition points are not uniformly spaced !

More than one definition for INL exists !

Will give two definitions here

Integral Nonlinearity (ADC)



Consider end-point fit line with interpreted output axis

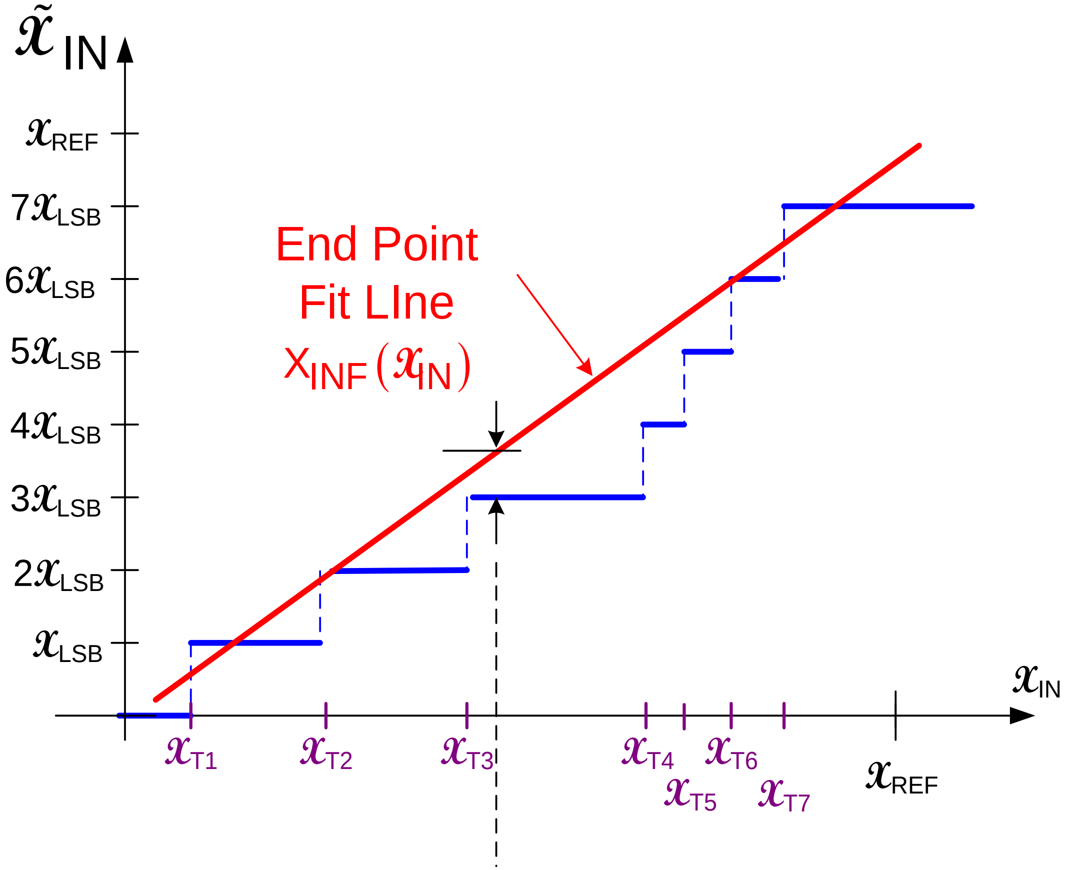
$$X_{INF}(x_{IN}) = m x_{IN} + \left(\frac{x_{LSB}}{2} - m x_{T1}\right)$$

$$m = \frac{(N-2)\, x_{LSB}}{x_{T7} - x_{T1}}$$

Integral Nonlinearity (ADC)

Nonideal ADC

Continuous-input based INL definition



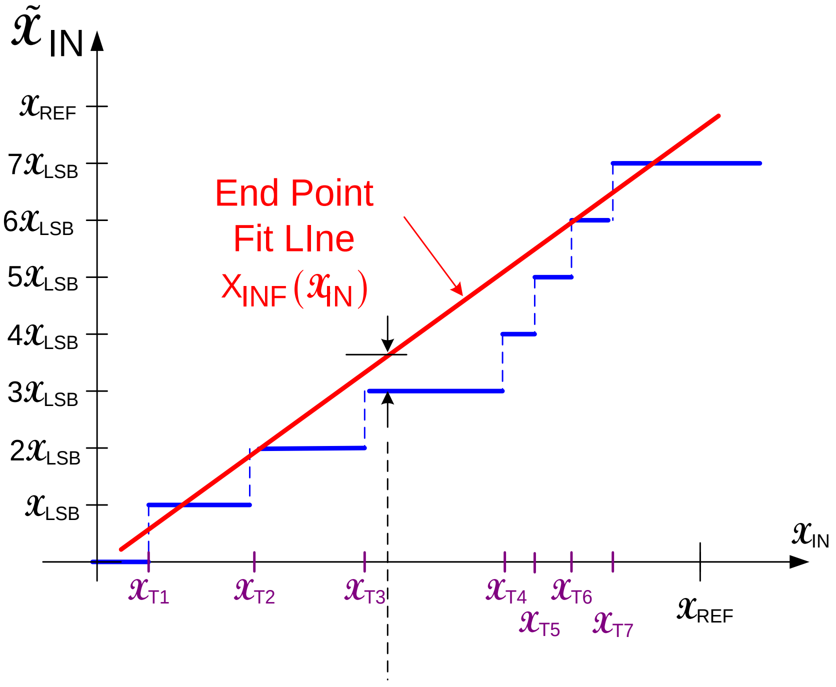
$$INL(x_{IN}) = \tilde{x}_{IN}(x_{IN}) - X_{INF}(x_{IN})$$

$$INL = \max_{0 \le x_{IN} \le x_{REF}} \left\{ \left| INL(x_{IN}) \right| \right\}$$

Integral Nonlinearity (ADC)

Nonideal ADC

Continuous-input based INL definition



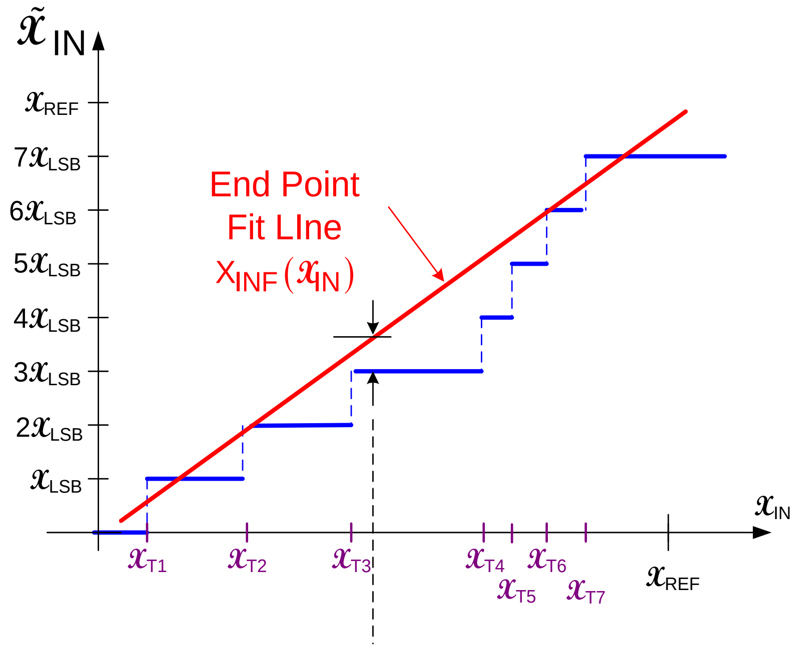
Often expressed in LSB

$$INL(x_{IN}) = \frac{\tilde{x}_{IN}(x_{IN}) - X_{INF}(x_{IN})}{x_{LSB}}$$

$$INL = \max_{0 \le x_{IN} \le x_{REF}} \left\{ \left| INL(x_{IN}) \right| \right\}$$

Integral Nonlinearity (ADC)

Nonideal ADC



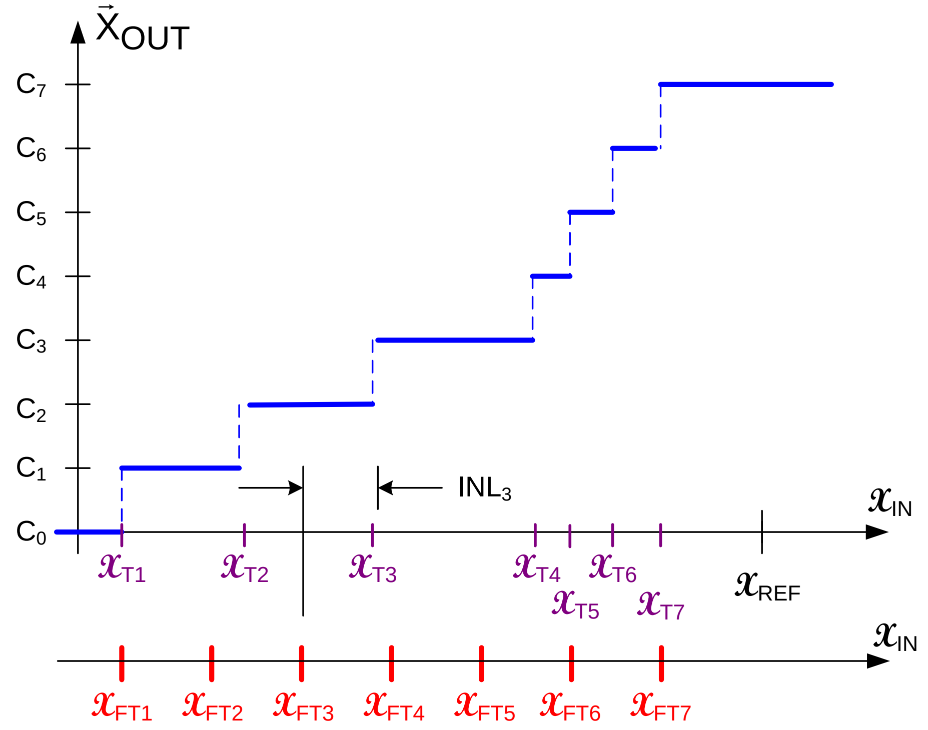
With this definition of INL, the INL of an ideal ADC is $x_{LSB}/2$ (for $x_{T1}=x_{LSB}$)

This is effective at characterizing the overall nonlinearity of the ADC but does not vanish when the ADC is ideal and the effects of the breakpoints is not explicit

Integral Nonlinearity (ADC)

Nonideal ADC

Break-point INL definition



Place N-3 uniformly spaced points between X_{T1} and $X_{T(N-1)}$ designated x_{FTk}

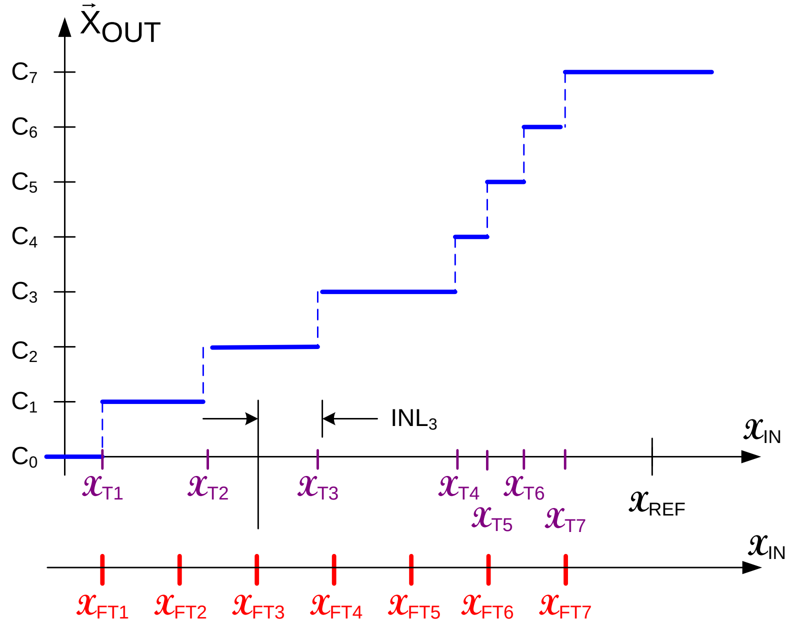
$$INL_k = x_{Tk} - x_{FTl} \qquad 1 \le k \le N\text{-}2$$

$$INL = \max_{2 \le k \le N-2} \left\{ \left| INL_k \right| \right\}$$

Integral Nonlinearity (ADC)

Nonideal ADC

Break-point INL definition



Often expressed in LSB

$$INL_k = \frac{x_{Tk} - x_{FTl}}{x_{LSB}} \qquad 1 \le k \le N-2$$

$$INL = \max_{2 \le k \le N-2} \{|INL_k|\}$$

For an ideal ADC, INL is ideally 0

Integral Nonlinearity (ADC)

Nonideal ADC

Break-point INL definition

$$INL_k = \frac{x_{Tk} - x_{FTk}}{x_{LSB}} \qquad 1 \le k \le N-2$$

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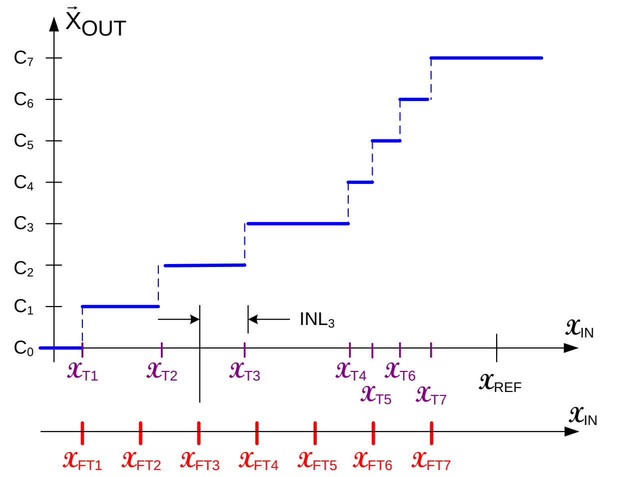


- INL is often the most important parameter of an ADC
- INL_1 and INL_{N-1} are 0 (by definition)
- There are N-3 elements in the set of INL_k that are of concern
- INL is a random variable at the design stage
- INL_k is a random variable for 0<k<N-1
- INL_k and INL_{k+j} are correlated for all k,j (not incl 0, N-1) for most architectures
- Fit Line (for cont INL) and uniformly spaced break pts (breakpoint INL) are random variables
- INL is the N-3 order statistic of a set of N-3 correlated random variables (breakpoint INL)

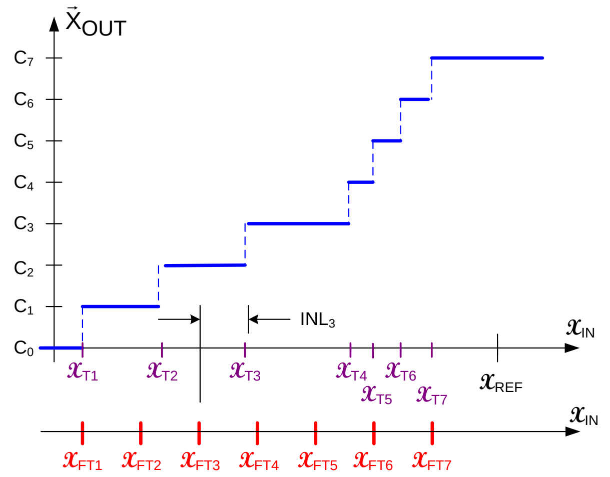
Integral Nonlinearity (ADC)

Nonideal ADC

Break-point INL definition

$$INL_k = \frac{x_{Tk} - x_{FTk}}{x_{LSB}} \qquad 1 \le k \le N-2$$

$$INL = \max_{2 \le k \le N-2} \{|INL_k|\}$$



- At design stage, INL characterized by standard deviation of the random variable
- Closed-form expressions for INL almost never exist because PDF of order statistics of correlated random variables is extremely complicated
- Simulation of INL very time consuming if n is very large (large sample size required to establish reasonable level of confidence)
  - -Model parameters become random variables
  - -Process parameters affect multiple model parameters causing model parameter correlation
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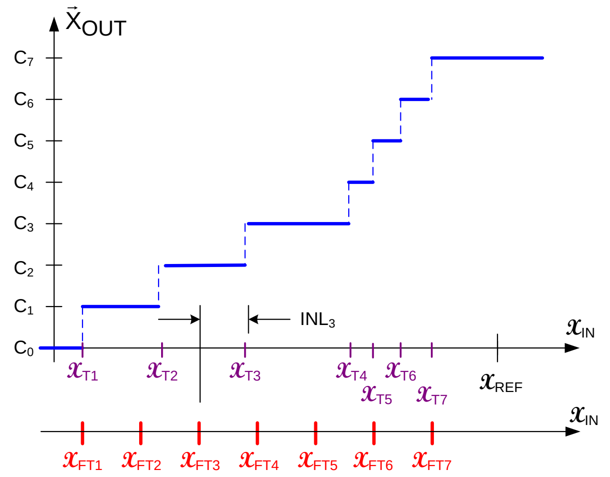
Integral Nonlinearity (ADC)

Nonideal ADC

Break-point INL definition

$$INL_k = \frac{x_{Tk} - x_{FTl}}{x_{LSB}} \qquad 1 \le k \le N-2$$

$$INL = \max_{2 \le k \le N-2} \{ |INL_k| \}$$



- INL can be readily measured in laboratory but often dominates test costs because of number of measurements needed when n is large
- INL is a random variable and is a major contributor to yield loss in many designs
- Expected value of INL_k at k=(N-1)/2 is largest for many architectures
- Major effort in ADC design is in obtaining an acceptable yield

INL-based ENOB

Consider initially the continuous INL definition for an ADC where the INL of an ideal ADC is $X_{LSB}/2$

Assume $$INL = \theta X_{REF} = \upsilon X_{LSBR}$$

where X_{LSBR} is the LSB based upon the defined resolution

Define the effective LSB by
$$\mathcal{X}_{LSBEFF} = \frac{\mathcal{X}_{REF}}{2^{n_{EQ}}}$$

Thus
$$INL = \theta 2^{n_{EQ}} X_{LSBEFF}$$

Since an ideal ADC has an INL of $X_{LSB}/2$, express INL in terms of ideal ADC
$$INL = \left[\theta 2^{(n_{EQ}+1)}\right]\left(\frac{X_{LSBEFF}}{2}\right)$$

Setting term in [ ] to 1, can solve for n_{EQ} to obtain

$$ENOB = n_{EQ} = \log_2\left(\frac{1}{2\theta}\right) = n_R - 1 - \log_2(\upsilon)$$

where n_R is the defined resolution

INL-based ENOB

$$ENOB = n_R - 1 - \log_2(\upsilon)$$

Consider an ADC with specified resolution of n_R and INL of v LSB

v	ENOB
½	n
1	n-1
2	n-2
4	n-3
8	n-4
16	n-5

Manufacturers of <u>Catalog</u> Data Converter Components

Table . 2004 Global Data Converter Market by Supplier

Company	2004 Rank	2004 $M	% Share	2003 Rank	2003 $M	% Share	Y/Y %
Analog Devices	1	1,018	40.5%	1	849	39.9%	20%
Texas Instruments	2	365	14.5%	2	265	12.4%	38%
Maxim Integrated Products	3	240	9.6%	3	205	9.6%	17%
National Semiconductor	4	90	3.6%	4	76	3.6%	19%
Linear Technology	5	54	2.1%	6	42	2.0%	28%
Renesas Technology	6	43	1.7%	5	46	2.2%	-6%
Philips Semiconductors	7	26	1.0%	10	21	1.0%	22%
Vishay Intertechnology	8	21	0.8%	9	24	1.1%	-11%
Fairchild Semiconductor Int'l	9	21	0.8%	8	27	1.3%	-21%
Intersil	10	19	0.8%	11	21	1.0%	-9%
Rohm	11	18	0.7%	12	21	1.0%	-12%
NJR	12	17	0.7%	14	16	0.7%	10%
Zarlink Semiconductor	13	15	0.6%	15	15	0.7%	2%
Fujitsu	14	13	0.5%	16	13	0.6%	-1%
Microchip Technology	15	11	0.4%	17	12	0.6%	-9%
Others		539	21.5%		478	22.4%	13%
Total		**2,511**			**2,130**		**18%**

Source: Company Reports, Databeans Estimates

United Business Media
EE Times

ADI's data converter business reflects a mixture of standbys and custom brews

By Stephan Ohr
Planet Analog
May 2, 2005 (6:38 PM EST)

Where engineers were once balancing resolution and conversion speed (along with power consumption and cost), Meaney said, they are now honing in on concepts like spurious-free dynamic range (SFDR), and only paying for the effective number of bits (ENOB) they need for their particular application - even if that number turns out to be something like 9 1/2.

New applications like Ultrasound Scanning, for example, demand high SNR and ENOB for high-image quality, but also something rarely specified before — over-range recovery — explained Kevin Kattmann, the product line director for high-speed converters (traveling with Meaney). Ultrasound imagers are effectively radar processors, using a phased-array antenna to bounce high frequency signals (256 of them) off of an object, and then creating an image based on the time it takes for each of these signals to bounce back to a sensor array at the antenna. Soft tissue will partially absorb and attenuate the signal and take a longer moment to return it; hard tissue, like bone, will show a much stronger reflected signal.

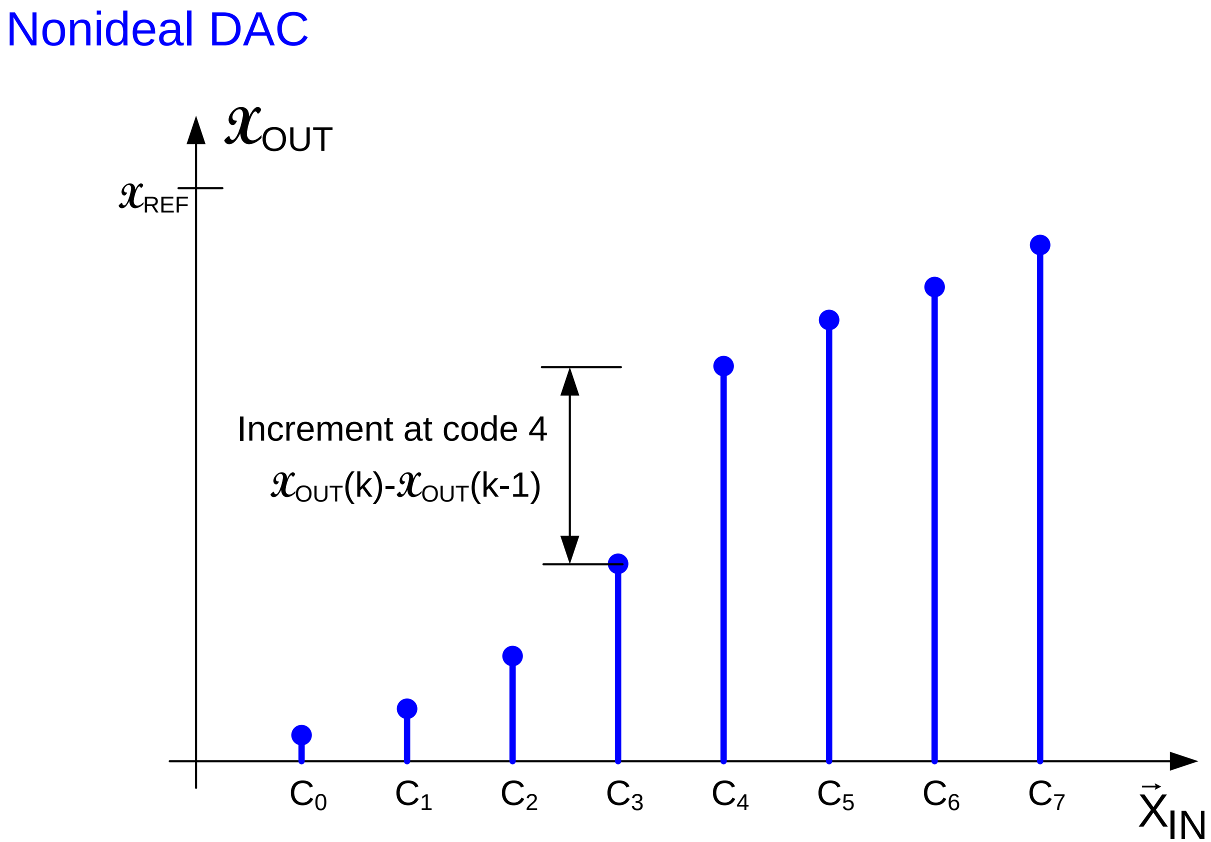
"The problem occurs when the scanner hits soft tissue right after encountering a solid object," Kattmann explained. "The front end gain amplifier must quickly reset, to crab the next set of samples. Otherwise, you'll have a blurred image." The front end of these converters need as much as 50 percent over-voltage range protection, with the ability to bounce right back to the proper input range, Kattmann said.

This is attention to the fine details of data converter applications is nothing new to Analog Devices, which holds a 45 percent share of $2.4 billion 2004 market according to recent assessments by Gartner Dataquest. Maxim Integrated Products (Sunnyvale, Calif.) is number two in this market, with a 15 percent share; Texas Instruments (Dallas) is number three with a 14 percent share. National Semiconductor Corp, (Santa Clara) and Linear Technology Corp. (Milpitas) continue to jockey for fourth and fifth positions.

Performance Characterization of Data Converters

- Static characteristics
  - Resolution
  - Least Significant Bit (LSB)
  - Offset and Gain Errors
  - Absolute Accuracy
  - Relative Accuracy
  - Integral Nonlinearity (INL)
  - Differential Nonlinearity (DNL)
  - Monotonicity (DAC)
  - Missing Codes (ADC)
  - Low-f Spurious Free Dynamic Range (SFDR)
  - Low-f Total Harmonic Distortion (THD)
  - Effective Number of Bits (ENOB)
  - Power Dissipation

Differential Nonlinearity (DAC)

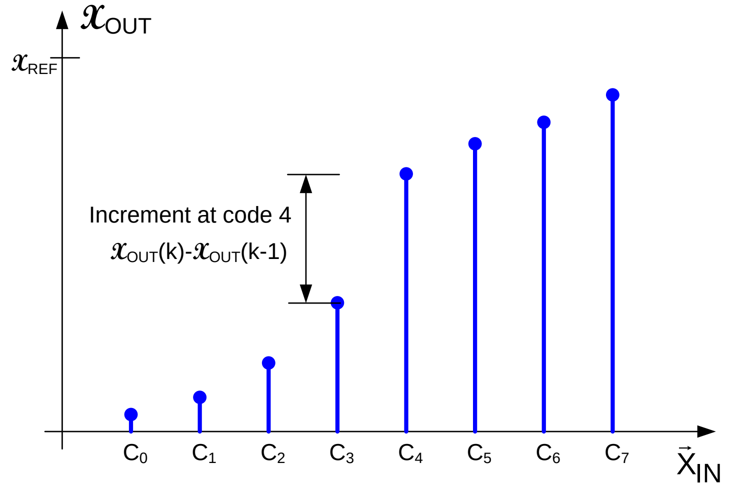


DNL(k) is the actual increment from code (k-1) to code k minus the ideal increment normalized to X_{LSB}

$$DNL(k)=\frac{X_{OUT}(k)-X_{OUT}(k-1)-X_{LSB}}{X_{LSB}}$$

Differential Nonlinearity (DAC)

Nonideal DAC



Increment at code k is a signed quantity and will be negative if $X_{OUT}(k)<X_{OUT}(k-1)$

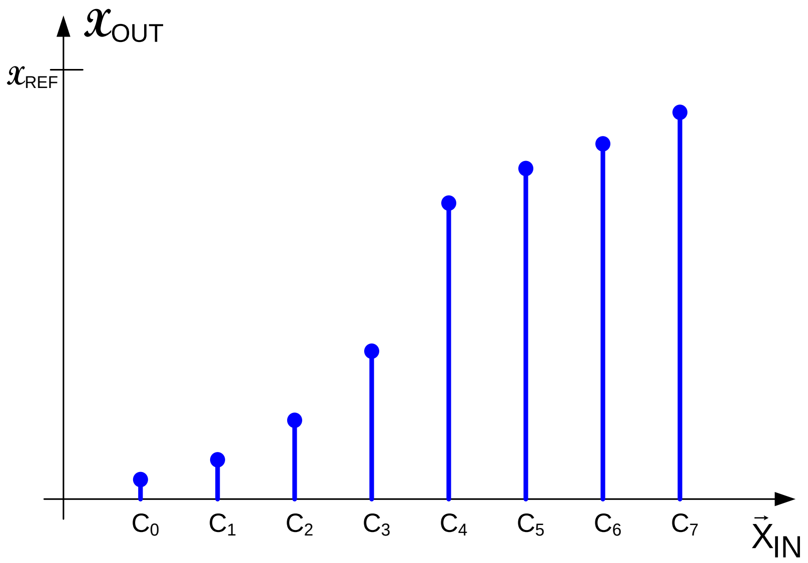
$$DNL(k)=\frac{X_{OUT}(k)-X_{OUT}(k-1)-X_{LSB}}{X_{LSB}}$$

$$DNL=\max_{1\le k\le N-1}\left\{\left|DNL(k)\right|\right\}$$

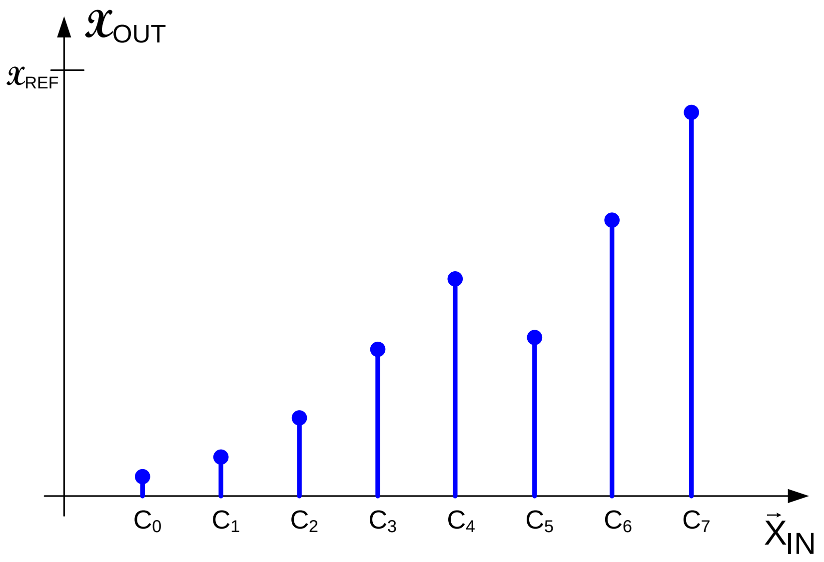
DNL=0 for an ideal DAC

Monotonicity (DAC)

Nonideal DAC



Monotone DAC



Non-monotone DAC

Definition:

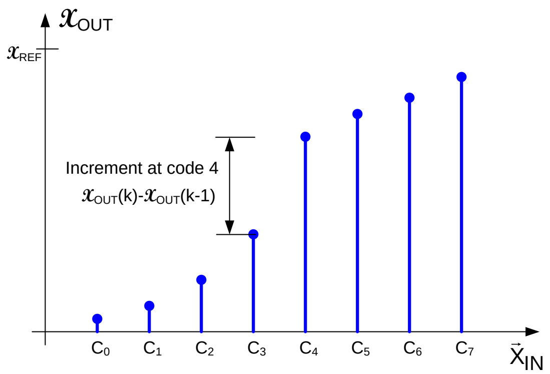
A DAC is monotone if $x_{OUT}(k) > x_{OUT}(k-1)$ for all k

Theorem:

A DAC is monotone if DNL(k)> -1 for all k

Differential Nonlinearity (DAC)

Nonideal DAC



Theorem: The INL_k of a DAC can be obtained from the DNL by the expression

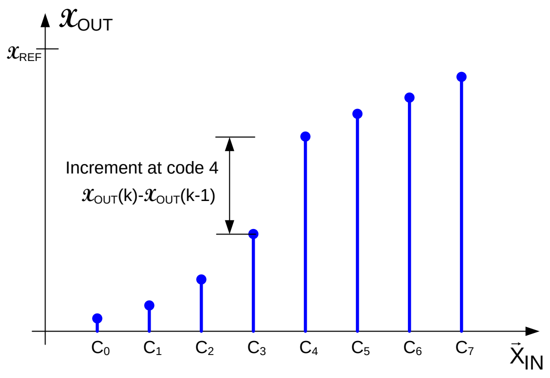
$$INL_k = \sum_{i=1}^{k} DNL(i)$$

Caution: Be careful about using this theorem to measure the INL since errors in DNL measurement (or simulation) can accumulate

Corollary: $DNL(k)=INL_k-INL_{k-1}$

Differential Nonlinearity (DAC)

Nonideal DAC



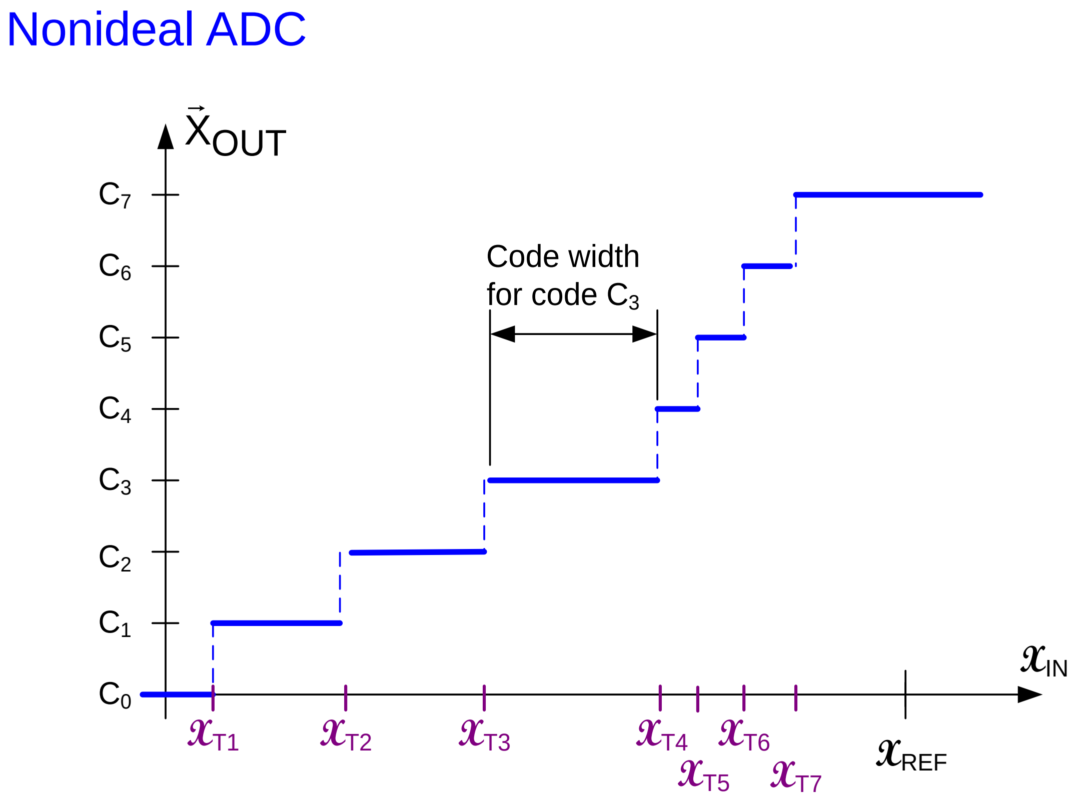
Theorem: If the INL of a DAC satisfies the relationship

$$INL < \frac{1}{2} X_{LSB}$$

then the DAC is monotone

Note: This is a necessary but not sufficient condition for monotonicity

Differential Nonlinearity (ADC)

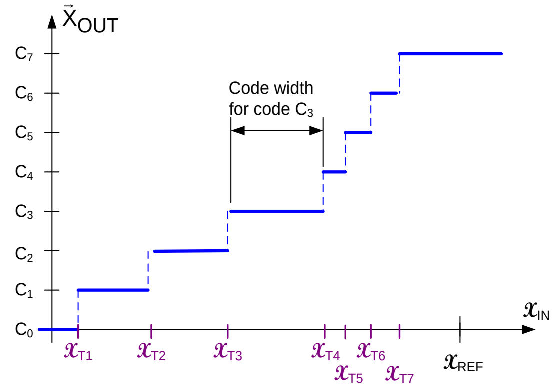


DNL(k) is the code width for code k – ideal code width normalized to X_{LSB}

$$\mathrm{DNL}(k)=\frac{x_{T(k+1)}-x_{Tk}-x_{LSB}}{x_{LSB}}$$

Differential Nonlinearity (ADC)

Nonideal ADC



$$DNL(k) = \frac{x_{T(k+1)} - x_{Tk} - x_{LSB}}{x_{LSB}}$$

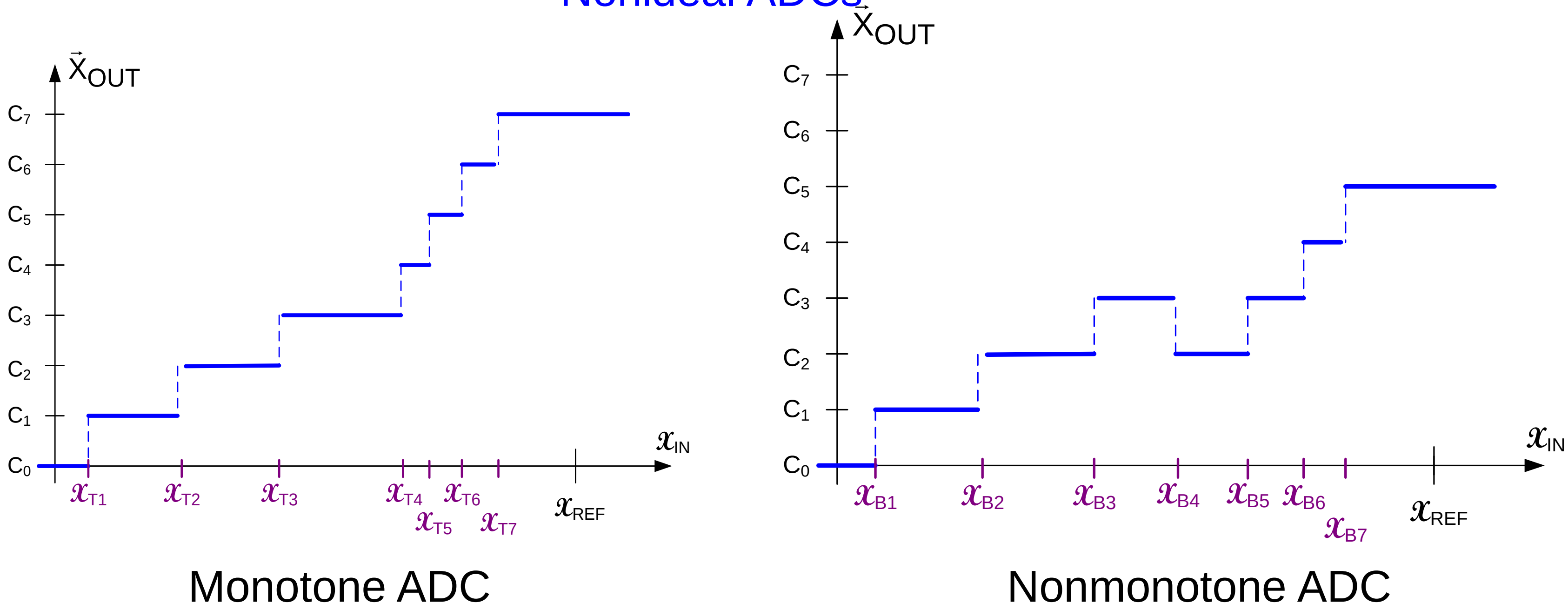
$$DNL = \max_{2 \le k \le N-1} \left\{ \left| DNL(k) \right| \right\}$$

DNL=0 for an ideal ADC

Note: In some nonideal ADCs, two or more break points could cause transitions to the same code C_k making the definition of DNL ambiguous

Monotonicity in an ADC

Nonideal ADCs



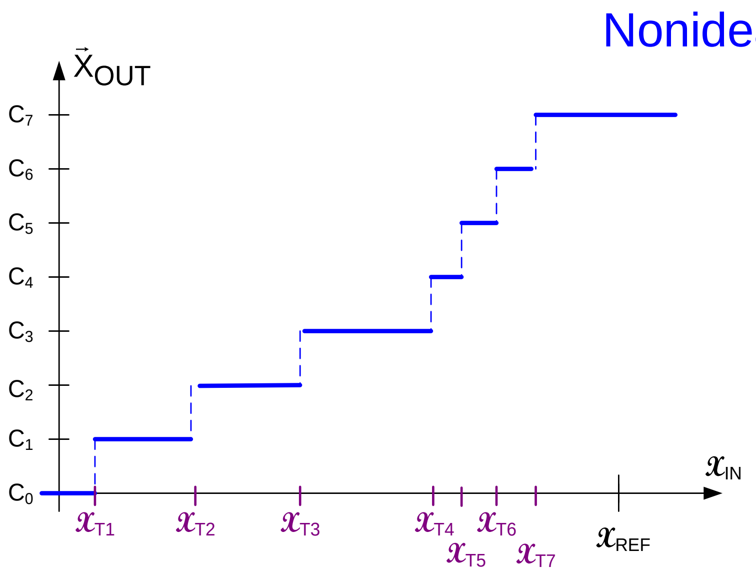
Definition: An ADC is monotone if the

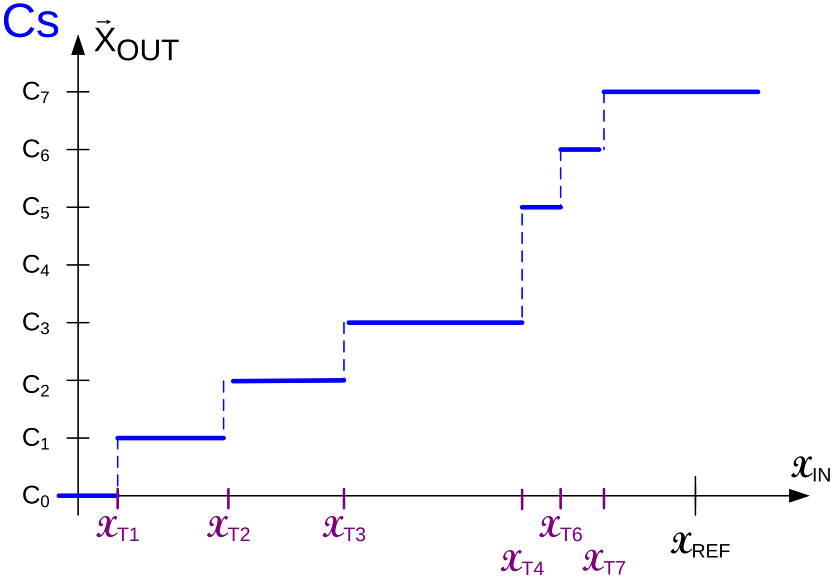
$$\vec{X}_{OUT}(x_k) \geq \vec{X}_{OUT}(x_m) \quad \text{whenever} \quad x_k \geq x_m$$

Note: Have used x_{Bk} instead of x_{Tk} since more than one transition point to a given code

Note: Some authors do not define monotonicity in an ADC.

Missing Codes (ADC)





No missing codes

One missing code

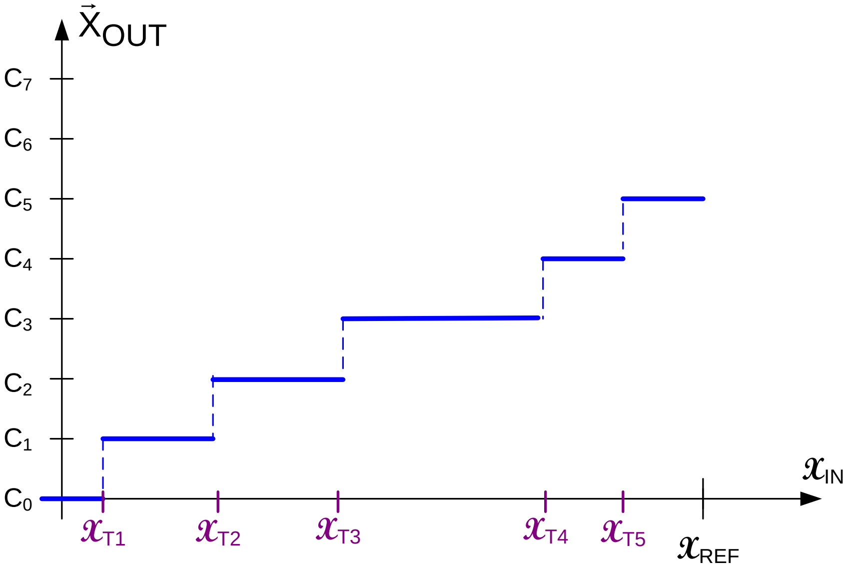
Definition: An ADC has no missing codes if there are N-1 transition points and a single LSB code increment occurs at each transition point. If these criteria are not satisfied, we say the ADC has missing code(s).

Note: With this definition, all codes can be present but we still say it has "missing codes"

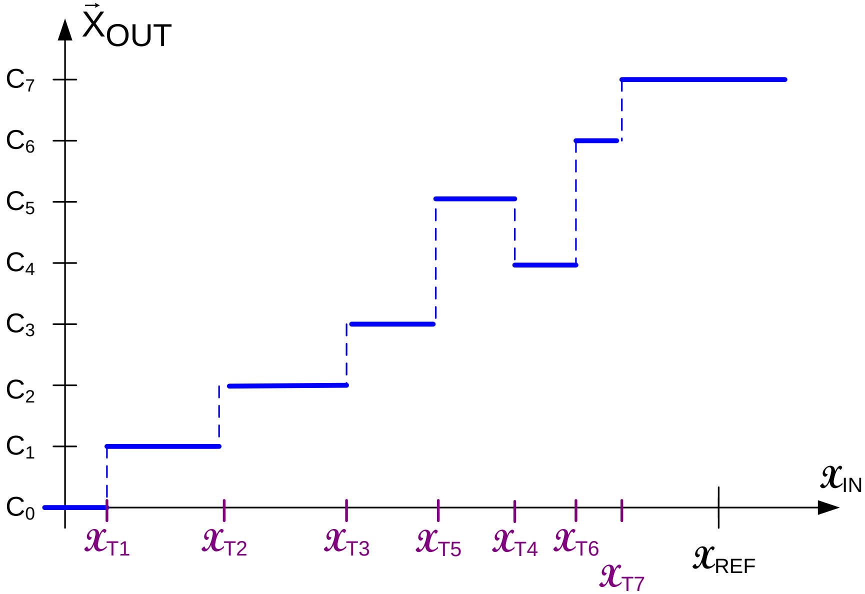
Note: Some authors claim that missing codes in an ADC are the counterpart to nonmonotonicity in a DAC. This association is questionable.

Missing Codes (ADC)

Nonideal ADCs

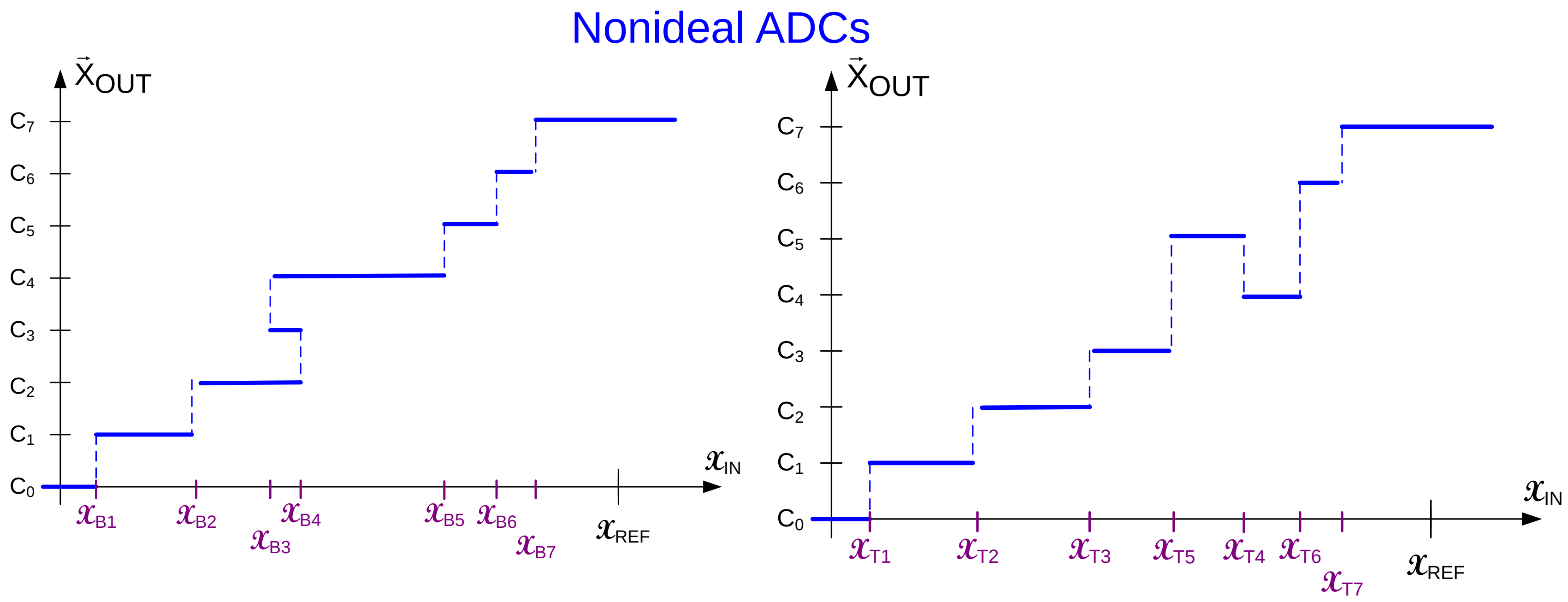


Missing codes



Missing code with all codes present

Weird Things Can Happen



- Multiple outputs for given inputs
- All codes present but missing codes

Be careful on definition and measurement of linearity parameters to avoid having weird behavior convolute analysis, simulation or measurements

Most authors (including manufacturers) are sloppy with their definitions of data converter performance parameters and are not robust to some weird operation

End of Lecture 28